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A review of dust emission dispersions in rock aggregate and natural stone quarries

Fugitive dust constitutes one of the most severe environmental problems in quarries because it escapes capture. This review aims to provide overview of dust concentration caused by quarrying by synthesizing the current knowledge. The 25 studies explored here were conducted in open-pit quarries or mines. Three main dust sources surfaced from the studies: drilling, crushing and hauling. Analysis revealed a range of dust concentrations caused by different quarrying operations. Crushing was the most significant dust source, while drilling caused the highest variation. Dust concentration decrease was observed with increasing distance, but the retention was incoherent due to local dust sources.

Keywords: dust; drilling; crushing; hauling; open-pit quarry

1. Introduction

Open-pit quarrying constitutes a core industry in many countries. Recycling, compensatory materials and the related technology have helped replace only a minority of the total consumption of the rock material [1]. Significant fugitive dust emissions appear when producing different types of rock products, such as aggregates in open-pit quarries. Fugitive dust refers to dust derived from indefinite sources or from more than one source [2]. These emissions can cause environmental, health, safety and operational effects mainly impacting the personnel of the quarry site but also the environment and community around the quarry. Inside the quarry, problems are generally related to labour safety and outside to adverse environmental impacts [3], like hygiene problems to buildings, constructions and vegetation [e.g. 4].

The United States Environmental Protection Agency [5] categorizes dust emission sources in open-pit quarries into process and fugitive dust sources. Process source emissions can be captured and subsequently controlled, e.g. through crushing inside a baghouse. Fugitive dust sources involve the re-entrainment of settled dust by

wind or machine movement, causing the dust to arise from the mechanical disturbance of granular material exposed to the air. Emissions from process sources should be considered fugitive unless the sources are contained in an enclosure with a forced-air vent or stack [5]. Fugitive dust poses one of the major problems in quarries because it is generated from unconfirmed sources, like quarry area and transportation, and it escapes capture [2].

Dust formation and spreading during open-pit quarrying are insufficiently explored environmental discomforts. The demand for producer-level environmental knowledge has increased and public authorities expect more detailed reports on environmental effects. Determining the concentration level and distance that the dust spreads, are essential when evaluating environmental effects.

The aim of this article is to provide a systematic overview of the dust concentration caused by open-pit quarrying, by synthesizing the current knowledge. Knowledge gaps, which may be addressed through further research, are identified. The essential terms are defined and the measurement methods and modelling are briefly introduced. The previous studies of dust measurement in the open-pit quarries and in ambient environment (surrounding the quarry boundary) are reviewed. The results are divided according to the quarrying process and dust concentration decreasing with increasing distance is evaluated. Finally the findings are presented on dust emission factors for different quarrying processes and the results from the different studies and generalization of the results is discussed. The work mostly excludes measurements concentrating on the related health effects. This review gathers international results concerning dust formation during open-pit quarrying and in addition provides data from the Finnish national studies [e.g. 6,7] which are presented internationally for the first time.

1.1 Quarrying processes

Natural stone quarries, hereafter *stone quarries*, produce stone blocks, which are detached from the bedrock by drilling, blasting, sawing or wedging. The aim is to detach stone blocks and the bedrock as intact as possible from the excavation without causing damage [8]. Drilling generates the majority of the dust formed in the processes employed in stone quarries [7,9].

Rock aggregate quarries, hereafter *aggregate quarries*, produce different-sized aggregates via crushing and sieving [10]. By drilling and blasting, the rock material is detached from the bedrock to fit in a crusher feeding bin. Larger rocks are fragmented with a hydraulic impact hammer before crushing. In aggregate quarries, the most dust-generating process is crushing and sieving. The drilling and blasting also causes dust emissions, but their impact is usually assumed insignificant compared to the most important dust-generating crushing and sieving [2].

Mining includes processes similar to aggregate quarries: drilling, blasting, hydraulic impact hammering, crushing and sieving. In some mines, e.g. in coal mines, the material is sheared from the parent rock. The crushed or sheared material continues in the process to the refiners, where the rock material is grinded and pulverized for the further procedures. Refiners are closed systems, in which dust formation is negligible in terms of environmental effects. The rest of the mining processes after pulverization include chemical phases, which form minor amounts of dust [11].

Some quarries follow different processes in their operations, but the drilling, blasting, hydraulic impact hammering and crushing are commonly employed with hard stone material, like granite. In quarrying softer rocks like sandstone, shearers or sawing are adopted to gain fragmented rock material or stone blocks.

Drilling produces dust when a drilling stem intrudes to the rock, for which reason drills are usually equipped with dry dust collection systems [9] in open-pit quarries. Underground mining employs wet suppression for dust prevention during the drilling [12].

During the crushing, a jaw or a cone movement triggers rock fragmentation by inducing a compressive stress on the material in the crusher. Rock fragmentation at localized high pressure during grain-jaw/cone and grain-grain contact contributes to the majority of the dust particles [13]. Dust formed during the crushing is commonly controlled with encapsulation or housing and water sprays.

All quarries include hauling of raw material and products. According to Reed [14], hauling produces significant amounts of dust (even 80-90%) in open-pit quarries. Kissell [12] reported that haul road dust is mainly formed during other processes in the quarry (e.g. crushing) and the hauling re-entrains the dust in the air. Hauling causes air flow, which lifts dust into the air. Dust is produced during the hauling due to the grain-grain pressure from the vehicles. Common dust prevention techniques for haul road dust include water or other water application, like salts and surfactants. Also soil cements, bitumens, films and their combinations are applicable to haul roads dust control [12].

1.2 Dust properties and behaviour

Dust is a generic term describing fine, solid particles which settle out under their own weight, but may remain suspended for some time [2,15,16]. The dispersion of suspended particles depends on the capacity of the dust particles to remain airborne, influenced by factors such as weight of particles, inter-particle forces and drag, and lift and movement imparted by the flow of air on the particles [15].

Dust particle size is the most frequently applied categorization property. Aerodynamic diameter is a commonly applied concept when defining the size of a dust

particle. The diameter refers to a spherical particle with the density of 1000 kg/m^3 that has the same settling velocity as the particle in question [15]. PM generally refers to particulate matter. PM_{10} and $\text{PM}_{2.5}$ are defined as PM with an aerodynamic diameter no greater than $10 \text{ }\mu\text{m}$ and $2.5 \text{ }\mu\text{m}$, respectively. According to US EPA [17], the total suspended particles (TSP) size range varies from $10 \text{ }\mu\text{m}$ to $100 \text{ }\mu\text{m}$, but a $30\text{-}\mu\text{m}$ aerodynamic diameter is commonly applied. Suspended particulate (SP) or suspended particulate matter (SPM) is defined as particles with an aerodynamic diameter of $30 \text{ }\mu\text{m}$ or less and is often qualified as equal to TSP. Inhalable particulate (IP) includes particles with an aerodynamic diameter of $15 \text{ }\mu\text{m}$ or less. $\text{PM}_{2.5}$ is referred to as fine particles or fine particulate (FP) [17]. Coarse particles refer to PM_{10} or larger particles.

Inhalable particulate fraction ends up in the nose or mouth through breathing, thoracic particulate fraction penetrates the head airways and enters the lung, and respirable particulate fraction penetrates beyond the terminal bronchioles into the gas-exchange region of the lungs [18]. Respirable fraction surrogates as alveolian fraction. Respirable or alveolian fraction is regarded approximately as $\text{PM}_{2.5}$, thoracic fraction as PM_{10} , and inhalable fraction as TSP [15].

According to US EPA [5], the variables affecting dust properties and behaviour are

- (1) material properties (including rock type, crusher feed size and distribution, moisture content),
- (2) process factors (including process throughput rate, type of equipment and process practices, size reduction rate, fines content) and
- (3) environmental factors including topography and climate.

Particle size, shape, chemical composition, mass concentration and density affect the behaviour of dust [15].

Belardi et al. [13] observed that the aerodynamic diameters of dust particles are independent of the crusher operating conditions. The maximum aerodynamic diameter of the particles formed during crushing was about 70-80 μm [13]. This is in accordance with the Office of the Deputy Prime Minister England [19], stating that crushing produces mainly coarse particles ($>30 \mu\text{m}$), which settle near, within 100 m of the dust source. Intermediate-sized particles (10-30 μm) are likely to travel up to 200-500 m. Smaller particles from quarries (less than 10 μm) represent a small proportion of dust and are deposited slowly [19].

Dust around quarries may resemble the mineralogical properties of the bedrock [3,20], but it is not identical since different minerals break down or are removed at different rates due to the quarrying processes [e.g. 2,18]. The relative proportions of minerals in road aggregates differed compared to those in the PM_{10} , produced during the hauling. Heterogeneities were observed in quartz and alkali feldspar concentrations of the PM_{10} [10,21].

Besides particle size, dust concentration decrease (i.e. dust retention) depends on the prevalent weather conditions. Wind speed and direction are essential. When wind speed remains under 1 m/s, the dilution and dispersion are minimal [6]. Smaller particles remain airborne longer, deposit slowly and spread wider, while larger particles deposit more quickly [19]. Rainfall increases dust removal from the air and the removal is more pronounced to larger particles [15]. Also, increase in relative humidity has been observed to decrease the dust concentration in the air [20].

In addition to environmental effects, dust exposure can be associated with serious health risks and several epidemiological studies have reported adverse health effects of exposure airborne particulate matter [e.g. 22]. Exposure to quarry dust has reported to have a detrimental effect on lung function [23,24]. The size of particles is

directly linked to the potential to cause health problems. Particles below 10 µm in diameter pose the greatest problems when penetrating into lungs, and even into bloodstream [25]. Both coarse and fine particle exposures have been positively associated with mortality, but exposure to smaller particles has stronger impacts on health than exposure to larger particles [26]. Adverse health effects are dependent on both exposure concentrations and length of exposure, and long-term exposures have larger, more persistent cumulative effects than short-term exposures [22,23]. Dust-related health effects include pneumoconiosis, cancer, systemic poisoning, hard metal disease, irritation and inflammatory lung injuries, allergic responses (including asthma and allergic alveolitis), infection and effects on the skin [18].

1.3 Measurements and modelling

Dust measurements are commonly conducted for regulatory purposes to ensure adequately controlled exposure. Critical parameters in dust measurements in open pit quarries include sampling location, time of the measurement and climatic factors like wind speed and direction, temperature and moisture [2]. In addition, important factors in dust measurements comprise sampling duration, sampling and analytical end methods (e.g. weighing), data handling and analysis, and supplementary data collection [27].

Five typical types of samples, according to Hinds [15], include source, ambient and background samples, occupational health-related samples and real-time dust measurements. Source samples measure dust concentrations deriving from the source emissions. Ambient samples aim at representing the concentrations in ambient environments caused by the dust source. Background samples measure the contribution of other sources to dust levels. Real-time dust measurements determine a dust profile over a set time period [15].

Petavratzi et al. [2] gathered common monitoring techniques from UK Environment Agency's [27] and US EPA's [28] documents and classified the techniques into seven categories:

- (1) Filter paper technique,
- (2) Particulate sampling trains,
- (3) Automatic paper tape instruments,
- (4) Continuous microbalance instruments,
- (5) Light scattering systems,
- (6) Size selective techniques and
- (7) Deposit gauges.

Appendix A applies this categorization while presenting dust measurements results in detail.

Dust monitoring techniques 1-6 constitute active techniques. According to Mineral Industry Research Organization [29], active techniques draw volumes of air for a designated time period to measure the amount (particle concentration and mass) and type of dust (particle size fraction) suspended in the air. Measurement results are concentrations; a measure of the amount of substance contained per unit of volume. Deposit gauges represent passive techniques based on the principle that coarse particles suspended in the air fall out either under the influence of gravity (dry deposition) or in contact with water droplets (wet deposition) [29]. Besides measurements, dust load in the environment can be evaluated via calculation with emission factors. An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant [30], for example kilograms of dust for every processed ton.

Modelling dust concentration is also commonly related to regulatory purposes and environmental permitting. There are several different commercial and non-commercial models available, which have been reviewed by Holmes and Morawska [31]. Dispersion modelling uses mathematical equations, describing the atmosphere, dispersion and processes within the dust plume, to calculate concentrations at various locations. The suitability of the models to particle dispersion modelling depends on the nature of the concentration desired. Factors affecting the choice of the model include the complexity of the environment, the dimensions of the model, the nature of the particle source, the computing power and time that is required and the accuracy and time-scale of the calculated concentrations desired [31]. However, US EPA has listed preferred models, which are AERMOD and CALPUFF Modelling Systems, BLP; CALIN3, CAL3QHC/CAL3QHCR, CTDMPPLUS and OCD [32]. Modelling dust concentration produced during open-pit quarrying has revealed, that site-specific meteorological conditions and both in-pit and surrounding terrain have strong influence on the predicted dust dispersion [e.g. 33-36]. Characterization of the dust emission source is essential, because mischaracterization of a source can impact modelled concentrations by an order of magnitude [37]. Also, some models are reported to perform more accurately than others, when the modelling has been compared to the measured concentrations near open-pit quarries [e.g. 36,38].

In-pit terrain causes re-circulatory airflows, which create micro climates within the quarry. It is evaluated, that between 30-70% of the fugitive dust emissions from quarrying activities retain within the quarry boundary [e.g. 34,35,37]. Location of the dust source in relation to the quarry benches and wind direction have been noticed to have an effect on dust dispersion [e.g. 33,34,39] and modelling has been used to develop barriers for reducing dust emissions [e.g. 39,40].

2. Reviewed studies

This review focuses on environmental effects and fugitive dust near or inside open-pit quarries. Measurements concentrating on health effects are largely excluded. The dust measurements cover the quarry area and/or the ambient environment or measurements concentrated on certain quarrying processes (e.g. drilling). The measurements included in this review applied stationary measurement locations. Personal sampling studies related to health effects were excluded.

A total of twenty five studies were reviewed. The results are reported via the main dust-producing process. Three different main dust sources are reported here: drilling, crushing and hauling. Twenty one studies had emphasis on one of these three main dust sources. Three studies indicated two different main dust sources. Junttila et al. [41] and Bada et al. [42] acquired results from drilling and crushing, and Chang et al. [43] from crushing and hauling. Degan et al. [44] included all three dust sources in their research. Some studies included other dust sources, e.g. storage piles. According to previous studies, they yield a minor contribution to dust concentration [2] and are excluded from the results reported here. The reviewed studies are presented in Table 1.

Table 1. Reviewed studies according to the main dust sources

Dust was measured with several different measuring techniques and setups. The majority of the studies conducted measurements at source, ambient and background measuring stations. The definitions for measuring stations differed between studies. The source station is typically located inside the quarry or within few tens of meters from it, but a several-hundred-meter distance was also used. Ambient stations located farther away from the quarry compared to the source measuring stations, typically over a hundred-meter distance. The background station was located at the upwind direction from the quarry and usually at a long (kilometres') distance. Dust concentration and

deposition measurement results are summarized in Appendix A. The results and measurement setups are reported here with the same accuracy as in the original studies.

When determining dust mass concentration decreasing with increasing distance, exponential dust retention curves were adopted due to the higher regression coefficient (R^2) values compared to linear retention regression coefficient. The dust retention curves were defined with Microsoft Excel and applied for calculating the distance in which the background concentration was achieved.

2.1 Dust formed during the drilling, crushing and hauling

The drilling studies gained mass concentrations ranging several orders of magnitude. Studies made at 2000s frequently reported lower source mass concentrations compared to measurements made in 1990s. Values from recent measurements varies approximately from 100 to 1000 $\mu\text{g TSP}/\text{m}^3$ and from 60 to 700 $\mu\text{g PM}_{10}/\text{m}^3$ [6,7,9;42]. Source mass concentration measured at 1990s varies from 500 up to 95,000 $\mu\text{g TSP}/\text{m}^3$ [41,45]. However, some exceptions appeared. Golbabaie et al. [46] gained mass concentrations similar to the highest TSP concentrations observed at 1990s, approximately from 80,000 to 110,000 $\mu\text{g TSP}/\text{m}^3$. Olusegun et al. [47] and Degan et al. [44] gained higher PM_{10} concentrations compared to other studies made at 2000s. PM_{10} mass concentrations were over 15,000 $\mu\text{g}/\text{m}^3$ and approximately 5000 $\mu\text{g}/\text{m}^3$, respectively.

According to Organiscak and Page [45], dust concentration decreases significantly within tens of meters from the drill, being approximately 20% of TSP source concentration. This is in accordance with the results reported by Olusegun et al. [47] and Sairanen [7]. Sairanen [7] measured background concentration within the distance of a few tens of meters from the drill. A concentration decrease with increasing

distance is also observed with longer distances and lower concentration levels [6], but the decrease is more pronounced in immediate surroundings of the drill.

Measurements near (less than 50 m distance) the crusher or inside the aggregate quarry or at the aggregate quarry boundary at downwind direction (if direction reported) are considered to represent the source concentration for crushing. Finnish aggregate quarries had the highest TSP source mass concentrations on average from almost 30,000 to below 40,000 $\mu\text{g}/\text{m}^3$ [41,48]. In Iran, stone crushing produced TSP (total dust) and $\text{PM}_{2.5}$ (respirable) almost 10,000 $\mu\text{g}/\text{m}^3$ and approximately 1200 $\mu\text{g}/\text{m}^3$, respectively [49]. Three studies conducted at aggregate quarries in India gained lower TSP mass concentrations from 1000 to about 4000 $\mu\text{g}/\text{m}^3$ [50-52]. TSP source mass concentration was same order of magnitude, approximately 1100 $\mu\text{g}/\text{m}^3$ and 3500 $\mu\text{g}/\text{m}^3$, also in studies conducted in Taiwan and Nigeria, respectively [20,42]. The lowest TSP source concentrations were measured at a gravel crushing site [43] and at a limestone mine and a granite quarry [3]. Both studies measured TSP mass concentration approximately from 100 to 1000 $\mu\text{g}/\text{m}^3$. The amount of crushing units was high (50, 72 and 40 units, respectively) in all studies conducted in India [50-52], but the capacity was modest, approximately 50 t/d compared to movable crushers. Average production rate of movable crushers in Europe is approximately 300 t/h. The amount of crushing units was high (29) also in the study conducted in Iran reported by Bahrami et al. [49]. The capacity of the crushers was not reported. The amount of workers, which was from five to eight in each crusher, implies that crushing capacity was modest also in study reported by Bahrami et al. [49] compared to crushing units operated with machinery, e.g. wheel loaders.

Junttila et al. [41] and [48] gained also the highest PM_{10} mass concentrations varying from approximately 3000 $\mu\text{g}/\text{m}^3$ to almost 36,000 $\mu\text{g}/\text{m}^3$. Olusegun et al. [47]

measured high PM₁₀ concentrations near crushing, almost 11,000 µg/m³. Degan et al. [44] gained PM₁₀ concentrations approximately 4400 µg/m³ and 5400 µg/m³ for primary and secondary crushing, respectively. Other researches gained lower PM₁₀ mass concentrations, roughly 1000 µg/m³ [20,51,52] or only few hundred µg PM₁₀/m³ [3,42,43].

Even though Chang et al. [43] had low TSP and PM₁₀ concentrations at the gravel processing site, the dust deposition amounts were the highest among all the studies measuring dust deposition. The average deposition was from approximately 9 up to almost 22 g/m²/month, while other studies [16,53,54] reported dust deposition from approximately 2 to 9 g/m²/month near the dust source. The dust deposition at the surroundings of the limestone quarry was lower than ambient dust deposition near other quarries [53]. Deposition studies were mainly conducted at longer distances (from hundreds of meters to kilometers) compared to mass concentration studies (less than 100 meters).

Haul road dust was measured in an open-pit basalt quarry [44], in four gravel crushing sites [43], in and near limestone quarry [55,56] and in an open-pit iron ore quarry [14]. The results were mainly similar to the TSP and PM₁₀ fractions that were available for comparison apart from results gained in the basalt quarry, in which the PM₁₀ mass concentrations were over 4000 µg/m³, being approximately four times higher compared to results gained in other studies reported here. Hauling produced TSP mass concentrations from approximately 1600 to almost 3000 µg/m³ and PM₁₀ from approximately 600 to over 1000 µg/m³ [14,43,55-57]. The lowest values were gained near a limestone quarry by Abu-Allaban et al. [56].

2.2 Dust concentration decrease with increasing distance

Dust concentration decrease evaluations were possible in seven studies. One study

covered dust concentration in a stone quarry [7] and one addressed dust concentration [51] and two dust depositions [53,54] in rock aggregate quarries. Three studies placed emphasis on hauling [14,55,57].

Dust concentration decreases rapidly within a few tens of meters from the drilling in the stone quarry (Figure 1). The ambient dust concentrations were measured at the same elevation (“same”, see Figure 1) as the drill and also at the higher elevation (approximately 6 m higher, “higher”, see Figure 1) on the next quarry bench of the stone quarry [7].

Figure 1. Dust concentrations at different distances at the same elevation (not reported or “same”) as the drilling and at higher elevation on next quarry bench (“higher”) of the stone quarry. Figure compiled from data by Olusegun et al. [47] and Sairanen [7]. Note log₁₀ scale for y-axis.

Larger-size fractions decrease faster compared to smaller ones (Figure 1). According to Sairanen [7] the background concentrations are achieved at distances of 55 m and 80 m for coarse (TSP, PM₁₀) and fine (PM_{2.5}) particles, respectively, when conducting ambient measurements at the same elevation with the drill. The background concentrations are achieved approximately at 40 m distance for all measured particle size categories, when conducting ambient measurements at higher elevations compared to the drilling [7]. Also Olusegun et al. [47] observed significant decrease in PM₁₀ mass concentration within few tens of meters: at 25 m distance the concentration was roughly only 25% of source concentration. [47].

Chang [20] and Olusegun et al. [47] reported dust concentration decrease with increasing distance, but according to Sivacoumar et al. [51], dust concentrations showed no systematic reduction with increasing distance. The analysis included all ambient measuring station results at all compass points around the aggregate quarry, but

restricting analysis to concentrations measured by Sivacoumar et al. [51] at a certain compass point (approximately east), the dust mass concentration decreasing with increasing distance becomes more pronounced (Figure 2).

Figure 2. Dust concentrations at different distances from crushing. Figure compiled from data by Chang [20], Sivacoumar et al. [51] and Olusegun et al. [47]. Note \log_{10} scale for y-axis.

According to the results gained by Sivacoumar et al. [51] the background concentrations are achieved at distances of 1040 m, 1210 m and 990 m for TSP, PM₁₀ and PM_{2.5}, respectively. Olusegun et al. [47] observed significant decrease in PM₁₀ mass concentration within few tens of meters from crushing, but the retention was not as distinct as it was for drilling. At 25 m distance dust concentration formed during the crushing was under 50% of the source concentration whereas the remaining dust concentration for drilling at the same distance was 25% [47].

The decrease in dust deposition with increasing distance was observed in several studies, e.g. Aatos [6], Martinsson [53] and Cattle et al. [54]. The deposition measuring distance varied from few hundred meters to almost ten kilometres (Figure 3).

Figure 3. Crushing dust deposition at different distances from a gold mine (three measurement lines, MLI-3; Cattle et al. [54]) and in two aggregate quarries (A and D; Martinsson [53]). Note \log_{10} scale for x-axis.

The inverse correlation of dust concentration and distance from the quarries is unobvious due to local dust sources (traffic), especially in quarry A [53]. Therefore the results from quarry A are excluded from further analysis of dust retention results. The background deposition is achieved at distance 5400-9500 m from the Australian gold mine [54] and 770 m from quarry D [53]. According to particle diameter analysis, a significant amount of dust deposited originates from local sources, because the average

modal diameter for the nearest (39 μm) and the background (22 μm) measuring station were both categorized as regional (15-50 μm) particles [54].

Reed [14] and Organiscak and Reed [55] both measured TSP, PM_{10} (thoracic) and $\text{PM}_{2.5}$ (respirable) dust concentrations at three different distances at two measurement lines beside haul roads in iron ore mine and limestone quarry, respectively. Reed [14] measured $\text{PM}_{2.5}$ concentrations with two different measuring techniques: a cascade impactor and a personal DataRAM (PDR) monitor. Docx et al. [57] measured TSP concentrations with same sampling setup as Reed [14] and Organiscak and Reed [55], but with different method. All three studies observed similar decreasing in concentration with increasing distance. The retention of dust was significant within a 30 m distance from haul road for both coarse (Figure 4) and fine (Figure 5) particles.

Figure 4. TSP and PM_{10} (thoracic) concentrations from hauling at different distances. Figure compiled from data by Reed [14]; Organiscak and Reed [55]; Docx et al. [57].

Figure 5. The $\text{PM}_{2.5}$ (respirable) concentrations from hauling at different distances. Figure compiled from data by Reed [14]; Organiscak and Reed [55].

The background concentrations are achieved approximately at distances 16 m and 11 m for TSP and PM_{10} , respectively [14,55]. Docx et al. [57] observed that TSP (mass of particulates) achieved background concentrations at distance 29 m. The background concentrations of fine particles are achieved approximately at distances 19 m and 10 m for cascade impactor and PDR-measurement [14]. Organiscak and Reed [55] results refer that $\text{PM}_{2.5}$ reaches background concentration at 19 m distance. Results gained by Reed [14] were highly consistent with study reported by Organiscak and Reed [55] and Docx et al. [57]. Results for Organiscak and Reed [55] and Docx et al.

[57] were construed from figures and therefore results for these studies are considered only indicative.

Abu-Allaban et al. [56] and Docx et al. [57] gained roughly half the concentration of PM₁₀ and TSP (see Appendix A), respectively, close to a haul road compared to results reported by Reed [14] and Organiscak and Reed [55]. The highest concentration beside a haul road was measured by Degan et al. [44], which was approximately 4300 µg PM₁₀/m³.

Dust concentrations decrease rapidly within the first 15 m from the haul road. Due to the effect of the dust plume of the haul truck, the background concentrations measured are higher than expected and therefore Reed [14] concluded that background concentration is reached approximately at the 30 m distance. Also, Organiscak and Reed [55] observed significant decrease in dust concentration at the 15 m distance and further concentration reduction at the 30 m distance from the haul road. Particle size analysis showed that the amount of PM₁₀ in total airborne dust from hauling was on average 15% [14]. A majority (at least 80%) of the airborne dust generated by the trucks was non-respirable [55].

Chang et al. [43] and Reed [14] concluded that unpaved haul roads comprise the major sources of fugitive dust and the effect of haul road is crucial even when compared to drilling and crushing. Unpaved roads account approximately for 45-55% of the total particulate emissions at the gravel processing site and windblown dust from the bare ground is the second most significant dust source, accounting for 20-40% of TSP emissions [43]. Olusegun et al. [47] observed the drilling as a dominant dust source compared to crushing.

Bluvshstein et al. [16] observed stable concentrations at the upwind location relative to those measured at the downwind location. The downwind TSP

concentrations correlated with the production in the quarry [16]. Also Almeida et al. [3] reported correlation between TSP generation and the amount of production.

Chang et al. [43] concluded that the silt (equal to or less than 75 μm in diameter) and moisture content of raw materials constituted the dominant factors affecting fugitive dust emissions. The greater the silt and lower the moisture content, the higher the concentration of fugitive dust formed [43]. Variation in local climatic conditions is observed to have an effect on dust concentrations. Wind speed and direction have a significant effect on results [e.g. 45].

2.3 The emission factors for quarrying processes

US EPA has defined emission factors for different quarrying processes. These processes were tertiary crushing, fines crushing, screening, fines screening, truck loading and unloading, conveyor transfer point and wet drilling. The emission factor for tertiary crushing is applicable to primary and secondary crushing as an upper factor limit. In the US EPA [5] emission factors, estimates for blasting are not presented because of an insufficient amount of data and unreliability of available tests.

Emission factor studies have been conducted in several different quarries processing limestone or granite. The collected emission data from different quarries was combined to represent typical quarrying processes. PM_{10} and $\text{PM}_{2.5}$ emissions from limestone and granite processing were assumed to be similar [5]. TSP emissions were calculated from the PM_{10} emissions by multiplying the PM_{10} concentration with factor 2.1 [58]. Other studies have determined emission factors [e.g. 6,43,59], but the US EPA emission factors are the most commonly applied ones. Appendix B presents emission factors in detail.

Emission factors were tested at laboratory with rotating drum and limestone samples by Petavratzi et al. [60]. The evaluated test parameters were flow rate, tumbling

time and sample mass. The results varied significantly: the percentage of the total dust mass compared to the test sample mass ranged from 0.04 to 0.9%. The tumbling time had a greater effect on the dustiness than the sample mass. Consequently, quarrying processes release higher dust levels with longer operating times. The preliminary control tests showed increasing dust loads with an increasing airflow rate drawn through the drum. The most critical parameter affecting the dustiness besides the tumbling time was the concentration of fine particles in the test sample [60].

Chakraborty et al. [59] conducted studies at the winter season (1997-1998) to evaluate the worst possible scenario of air pollution due to low atmospheric ventilation. Aatos [6] measured nine days and analysed the results from five days, excluding the rainy and calm (wind speed under 1 m/s) ones. Both Chakraborty et al. [59] and Aatos [6] applied the highest measured values and Chang et al. [43] the average downwind concentration when determining emission factors.

US EPA [5] and Chang et al. [43] determined emission factors mainly for different processes. The PM₁₀ emission factors for loading and unloading raw and crushed material were similar enough for comparison. The PM₁₀ emission factors for raw material loading were 8.0×10^{-6} kg/t [5] and 0.48 kg/t [43]. The emission factors for crushed product loading were 5.0×10^{-5} kg/t [5] and 0.56 kg/t [43]. The emission factors obtained from the gravel processing site were significantly higher (tens of thousands of times higher) compared to US EPA emission factors. Chang et al. [43] had TSP/PM₁₀ ratio 1.4...1.7 whereas US EPA had 1.7...4.1, when calculating ratios from the reported emission factors.

Chakraborty et al. [59] and Aatos [6] had an emission factor for overall quarry available for comparison. Chakraborty et al. [59] gained an emission factor for TSP,

which was ten times higher compared to the emission factor for PM₁₀ reported by Aatos [6].

3. Discussion

There were restricted amount of studies available that met the criteria concerning the aim of this review. The reviewed literature employed several different sampling setups. Dust concentrations were measured in different quarries with several measuring techniques, which also complicates the comparison of results. As pointed out by Petavratzi et al. [2], the quarrying operations are quite diverse and it is difficult to define an absolute standard for measurements applicable to all quarries. Material properties, quarrying methods, operational variations and locations constitute some of the parameters that are different for every quarry. Climatic conditions have been widely recognized as a factor crucially affecting dust concentrations [e.g. 6,16,50,54]. Climatic conditions vary from site to site due to differences in location and microclimatic structure. Quarries have to be assessed in accordance with particular characteristics. The results gathered here support this. The background concentrations varied significantly, for example, being multiple times higher in locations such as India [51] and Australia [54], compared to Sweden [53] and Finland [7].

3.1 Dust concentrations and depositions

According to the dust measurement studies reviewed in this article, the variation in dust mass concentrations is significant for both drilling and crushing, which implies that dust concentrations at quarries and their ambient environments are highly site specific. Since open-pit quarrying facilities are dynamic operations exposed to changing weather conditions, day-to-day dust levels can be highly variable [55]. The dust concentration variation for TSP is larger for drilling than for crushing, ranging from 100 up to 110,000

$\mu\text{/m}^3$. For crushing, the TSP concentration varies from 100 to almost 40,000 $\mu\text{g}/\text{m}^3$. Despite the large variation, the dust measurements near drilling gained results largely hundreds of $\mu\text{g TSP}/\text{m}^3$ whereas near crushing the dust mass concentrations were usually several thousands of $\mu\text{g TSP}/\text{m}^3$. This implies that crushing produces more dust compared to drilling, which is in accordance with Petavratzi et al. [2].

Dust measurements close to haul roads showed smaller variation in results (TSP 1400-3000 $\mu\text{g}/\text{m}^3$ and PM_{10} 1000-4300 $\mu\text{g}/\text{m}^3$) compared to drilling and crushing measurements. The lower variation may be explained by the restricted amount of studies all made after 2000 (six studies concentrating on hauling). Also, the similarity of dust source may be higher in hauling studies (vehicles passing by and lifting dust into the air) compared to drilling and crushing (different equipment with differing production capacities).

The studies from 1990s frequently reported higher dust concentrations than studies completed after 2000. However, some exceptions appear [e.g. 44,46]. The dust mass concentrations caused by drilling were lower compared to those from crushing according to measurements made in 2000s. In the earlier measurements, the difference was not distinct. This is probably due to the enhanced dust prevention techniques and development of quarrying equipment and processes. Also some of the dust measurements made near drillings in 1990s may have been affected by other dust sources in the quarry area.

The reported results of the dust depositions were consistent, whereas there was high variation in TSP mass concentrations for crushing studies. The variation was lowest when the sampling locations were far away from the sources (several hundred meters) and the duration time for sampling was long (several months). This indicates that dust deposition results represent well the overall dust load in the explored area.

However, the contribution of the actual quarry production to the dust load remains unclear.

Some of the studies described the measurement setup on a level insufficiently detailed for the scope of this review [e.g. 41,45,47,49]. In addition, SPM was used as a surrogate to PM₁₀ by Olusegun et al. [47], which increases the uncertainty of the comparison of their results to other studies due to the differing definition. Also the restricted amount of studies (e.g. studies made at 1990s) increases the uncertainty of comparison. The ability to extrapolate these results to other quarries seems inconclusive. Even though the results could not be fully generalized, the concentration results revealed a range within which the dust concentration varies in the stone and aggregate quarries. The variation in concentration remained too high, especially for drilling, to make reasonable evaluation of environmental effects. The higher values are however applicable as upper limit values when evaluating the acceptable level of environmental effects in the vicinity of a quarry.

Measurements at several different quarries according to the same procedure are needed for comparing the results and to verify the possibility of extrapolation. Measurements at different distances are required to be comparable, e.g. the measurements are from the same climatic and production conditions. Controlling the variables which affect dust concentration is required to gain results generalizable to other quarries.

Sampling with short sampling intervals (seconds) is recommended for yielding a large amount of data in a short time period. It allows comprehending the effects of weather condition when observing weather parameters at the same time. Short sampling intervals also enable measuring at several sampling locations at the same climatic conditions, which increases certainty when comparing results.

3.2 Retention of dust

Several studies have observed dust mass concentration decreasing with increasing distances, but retention was not always obvious. The highest concentration or deposition of dust was mainly measured at the nearest measurement locations from the source in all the reviewed studies, which is expected. Also the retention was more pronounced in the immediate surroundings (within few tens of meters) from the dust source, when interfering local dust sources lacked. When the samplers located far from the quarry, the results showed no entirely consistent decrease of dust concentration due to the significant impact of local dust sources affecting the results. The evaluation of the distance needed for achieving background concentration or deposition varied from 10 meters [14] to 9000 meters [54]. According to modelling results, the impact zone (distance where $200 \mu\text{g TSP}/\text{m}^3$ is achieved) of quarry dust varies from 150 m to 2700 m and from 70 m to 1400 m for uncontrolled crushing and after implementing dust control measures, respectively [52]. The background concentration was reached at shorter distance when measuring at higher elevations compared to the dust source [7], which is in accordance with the findings gained via modelling stating that 30-70% of the fugitive dust emissions from quarrying activities retain within the quarry boundary [e.g. 34,35,37].

The background concentrations of TSP, PM_{10} and $\text{PM}_{2.5}$ are achieved mainly within the hundred-meter distance (hauling and drilling), except for crushing. Therefore, in terms of environmental effects in the ambient environment of quarries, the crushing is more essential compared to hauling and drilling. However, the dust concentration caused by drilling showed higher variation compared to results gained near crushing and therefore drilling may be determinant in dust production in some quarries.

The dust deposition decrease measured by Martinsson [53] was approximately ten times the corresponding values gained by Cattle et al. [54]. The lower retention rate for dust deposition gained by Cattle et al. [54] compared to the retention rate gained by Martinsson [53], may be explained by measuring distances which ranged from 700 to 9000 m and from 10 to 400 m, respectively. The longer distances enable more interfering dust sources, which affects the results.

Measurements at different distances from the dust source are needed to define dust retention curves to evaluate the distances dust spreading in the atmosphere. The retention of dust concentration requires measurements performed at several relatively short distances (approximately from tens of meters to few hundreds of meters) to control factors affecting the measurement like microclimatic conditions and local dust sources.

3.3 Emission factors

The US EPA emission factors estimate lower dust concentrations compared to other emission factors [6,43,59]. The US EPA emission factors may yield, at some circumstances, an underestimation of dust concentration when used as a source parameter in modelling the ambient environment of a planned quarry. Emission factors should only be adopted when more accurate data is unavailable [58].

In US EPA [5] emission factors for TSP were calculated from PM₁₀ emission factors. The emission factors had varying TSP/PM₁₀ ratios, which in some cases differed from the ratio (2.1) which was announced to be used in calculations [58]. The extrapolation of the TSP emission factor from the PM₁₀ emission factor may have had an effect on the reported emission factors. Also the significance of the rock type processed was assumed to be negligible. Limestone and granite may behave differently

in quarrying processes because different minerals break down at different rates due to the quarrying processes.

Due to the large variation in emission factors and the development of quarrying equipment (e.g., enhancement of dust prevention techniques), the emission factors should be verified in the future to neglect the misvaluation when modelling dust concentrations. Also the effect of process duration, rock type and raw material fine content are parameters which impact the emission and these factors should be included in the examination.

According to dust concentration results reviewed here, the TSP concentration is from 1.5 to 15 times the concentration of PM₁₀. Majority of the studies which measured TSP and PM₁₀ [e.g. 43,48,51] showed that the TSP concentration is approximately 2 to 4 times the concentration of PM₁₀. Chakraborty et al. [59] gained an emission factor for TSP which was ten times higher compared to the emission factor for PM₁₀ reported by Aatos [6]. This implies that Chackraborty et al. [59] determined a higher emission factor for the overall quarry compared to Aatos [6]. This is also in accordance with the concern that crushing produces significant amounts of dust compared to drilling [2,42].

4. Conclusions

This review reports dust concentration ranges derived from selected studies of drilling, crushing and hauling dust. The results varied significantly from 100 to 110,000 µg TSP/m³ near the dust source. Upper values are applicable to conservative evaluations when evaluating environmental effects caused by a planned quarry.

The results show that crushing has the most significant effect on dust concentration caused by quarrying. The highest dust concentrations and depositions were mainly measured at aggregate quarries and also emission factors were higher for aggregate quarries compared to natural stone quarries.

The measurements in the 1990s yielded higher concentrations than those made in the 2000s. This is probably due to the enhanced dust prevention techniques and development of quarrying equipment and processes.

Dust concentration decrease with increasing distance was observed, but the retention was not always obvious due to local dust sources affecting the results. The evaluation of the distance needed for achieving background concentration or deposition varied from 10 meters [14] to 9000 meters [54].

Quarries produce mainly coarse particles, which is supported by all studies measuring fine and coarse particle concentration. TSP concentration was approximately 2 to 4 times the concentration of PM₁₀.

Measurements at several different quarries according to the same procedure are needed when comparing the results. Sampling with short sampling intervals (seconds) is recommended for yielding large amounts of data in short time periods and for enabling the measurements at several sampling locations at the same climatic conditions.

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Table 1. Reviewed studies according to the main dust sources.

Figure 1. Dust concentrations at different distances at the same elevation (not reported or “same”) as the drilling and at higher elevation on next quarry bench (“higher”) of the stone quarry. Figure compiled from data by Olusegun et al. [47] and Sairanen [7]. Note \log_{10} scale for y-axis.

Figure 2. Dust concentrations (Note: \log_{10} scale) at different distances from crushing. Figure compiled from data by Chang [20], Sivacoumar et al. [51] and Olusegun et al. [47]. Note \log_{10} scale for y-axis.

Figure 3. Crushing dust deposition at different distances from a gold mine (three measurement lines, ML1-3; Cattle et al. [54]) and in two aggregate quarries (A and D; Martinsson [53]). Note \log_{10} scale for x-axis.

Figure 4. TSP and PM_{10} (thoracic) concentrations from hauling at different distances. Figure compiled from data by Reed [14]; Organiscak and Reed [55]; Docx et al. [57].

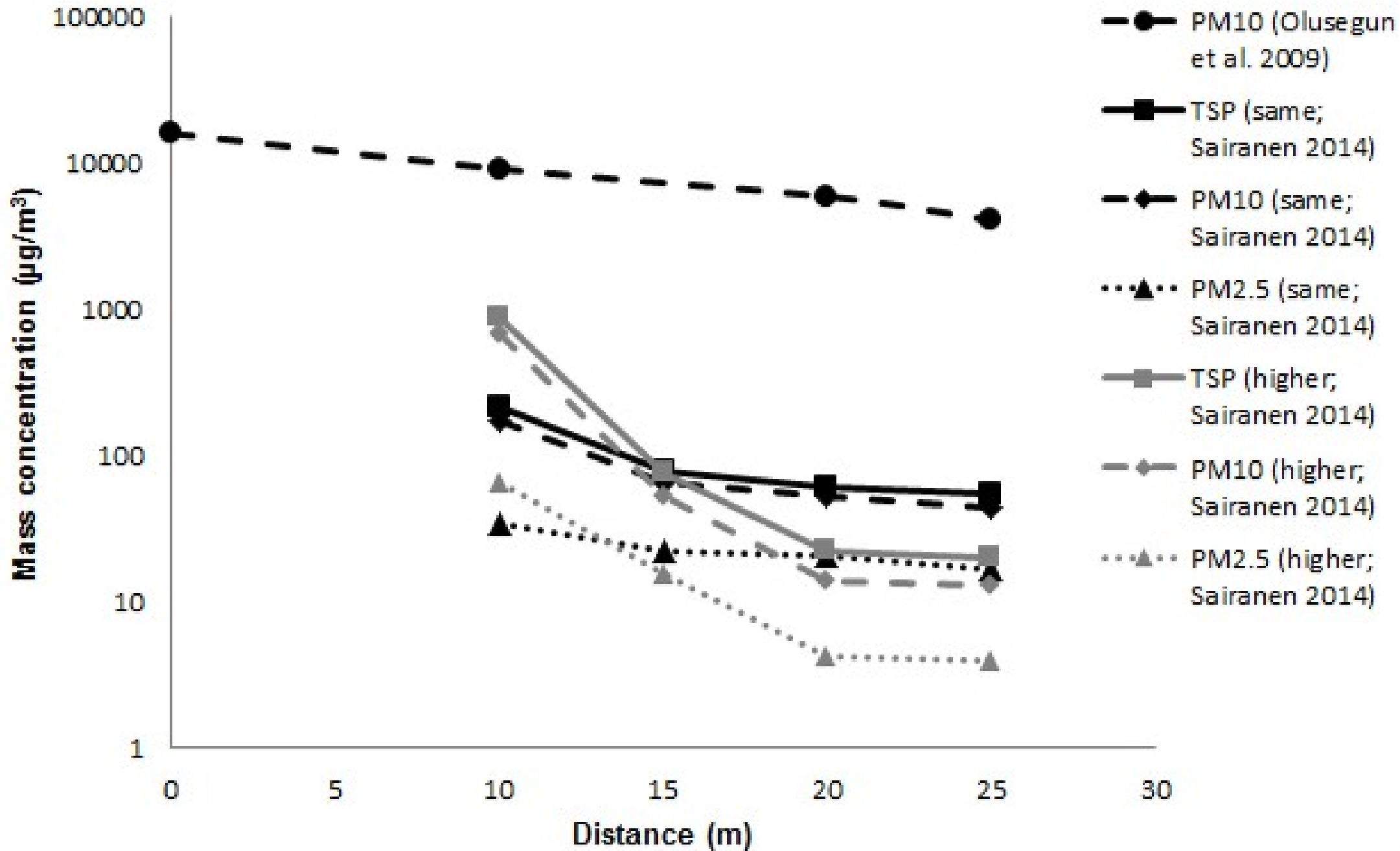
Figure 5. The $PM_{2.5}$ (respirable) concentrations from hauling at different distances. Figure compiled from data by Reed [14]; Organiscak and Reed [55].

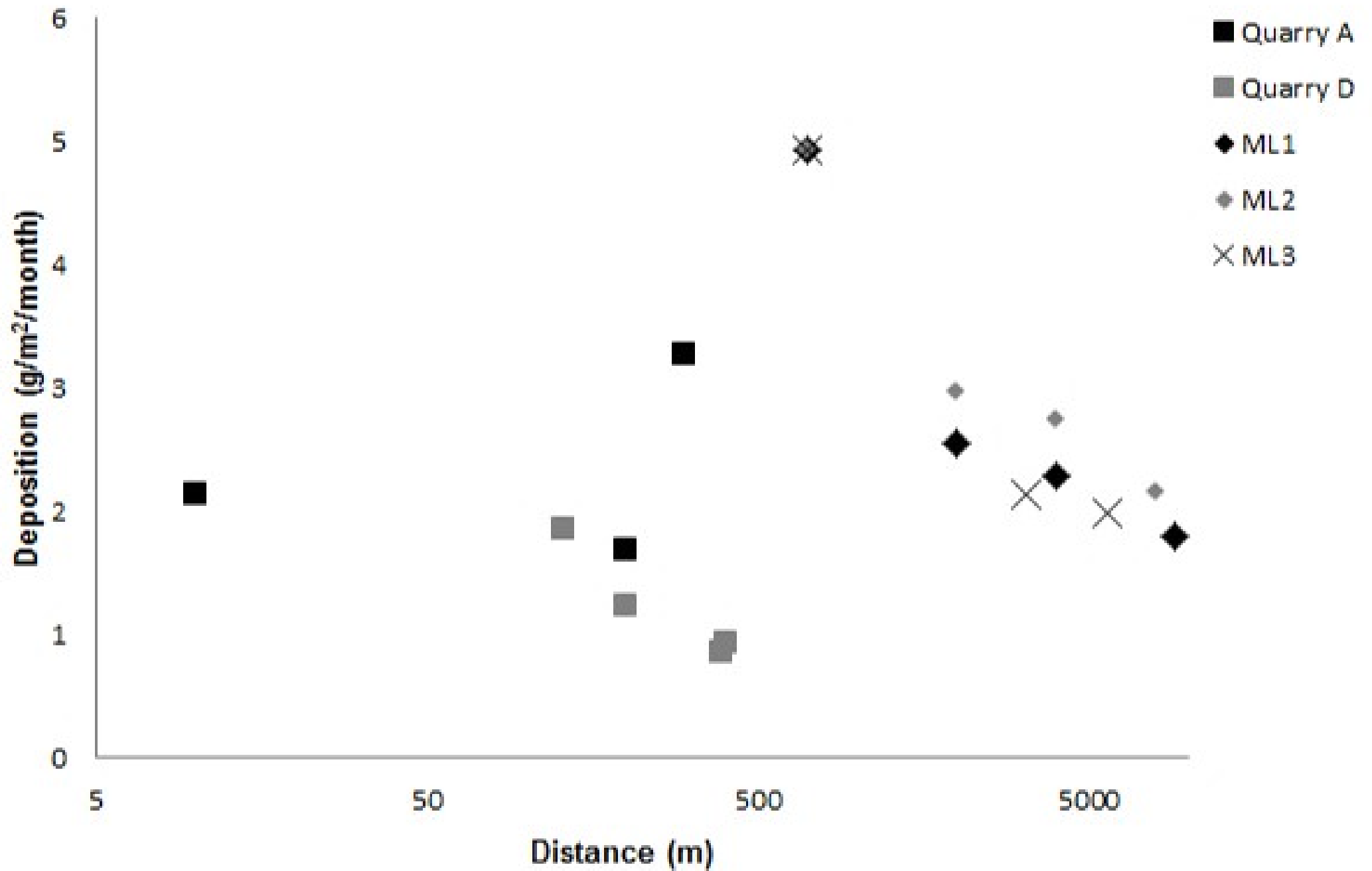
Appendix A. Dust concentration and deposition results in measurements made in open pit quarries or similar sites. Concentration results given in parenthesis are the observed ranging of results.

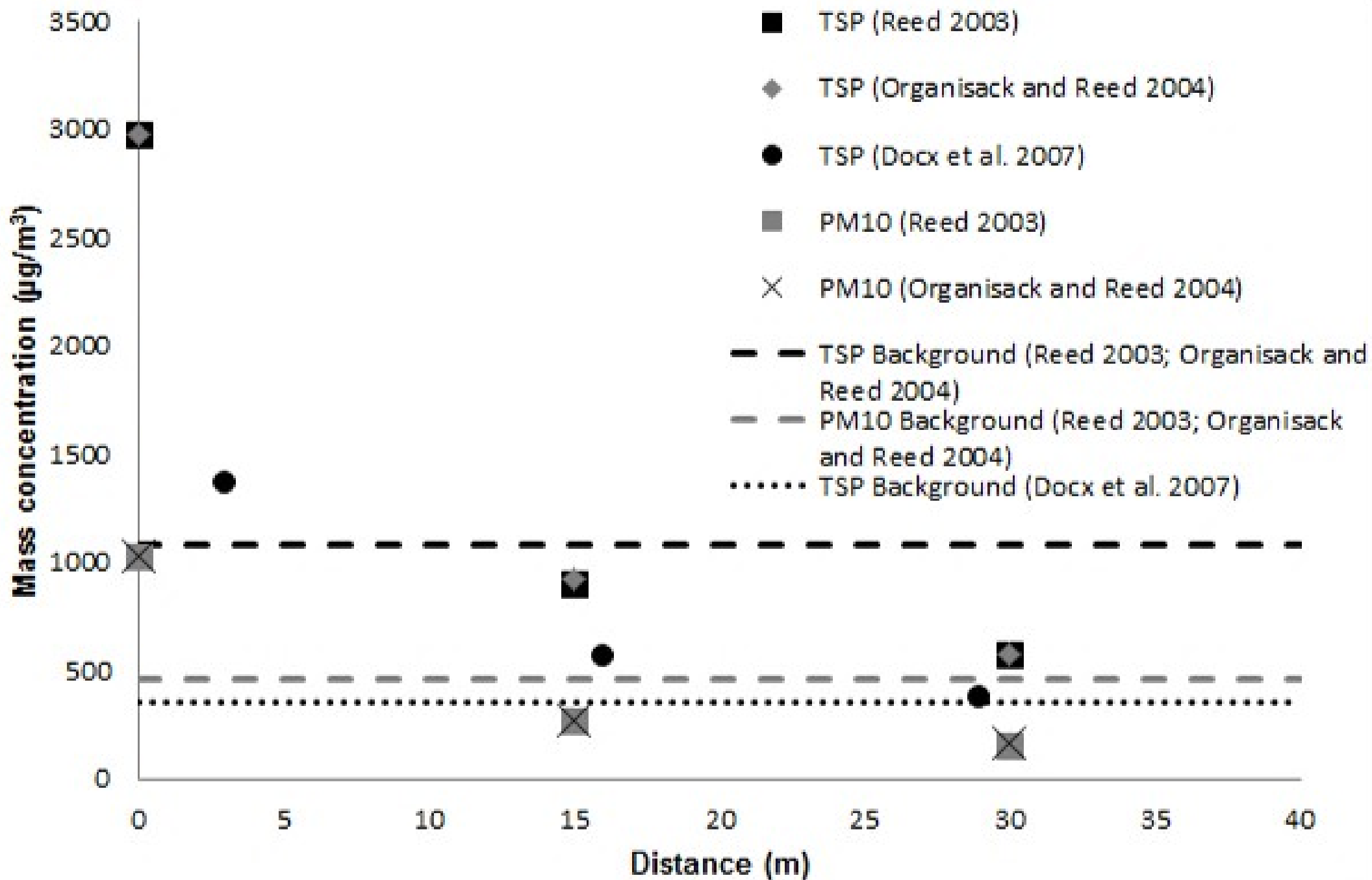
Appendix B. Emission factors.

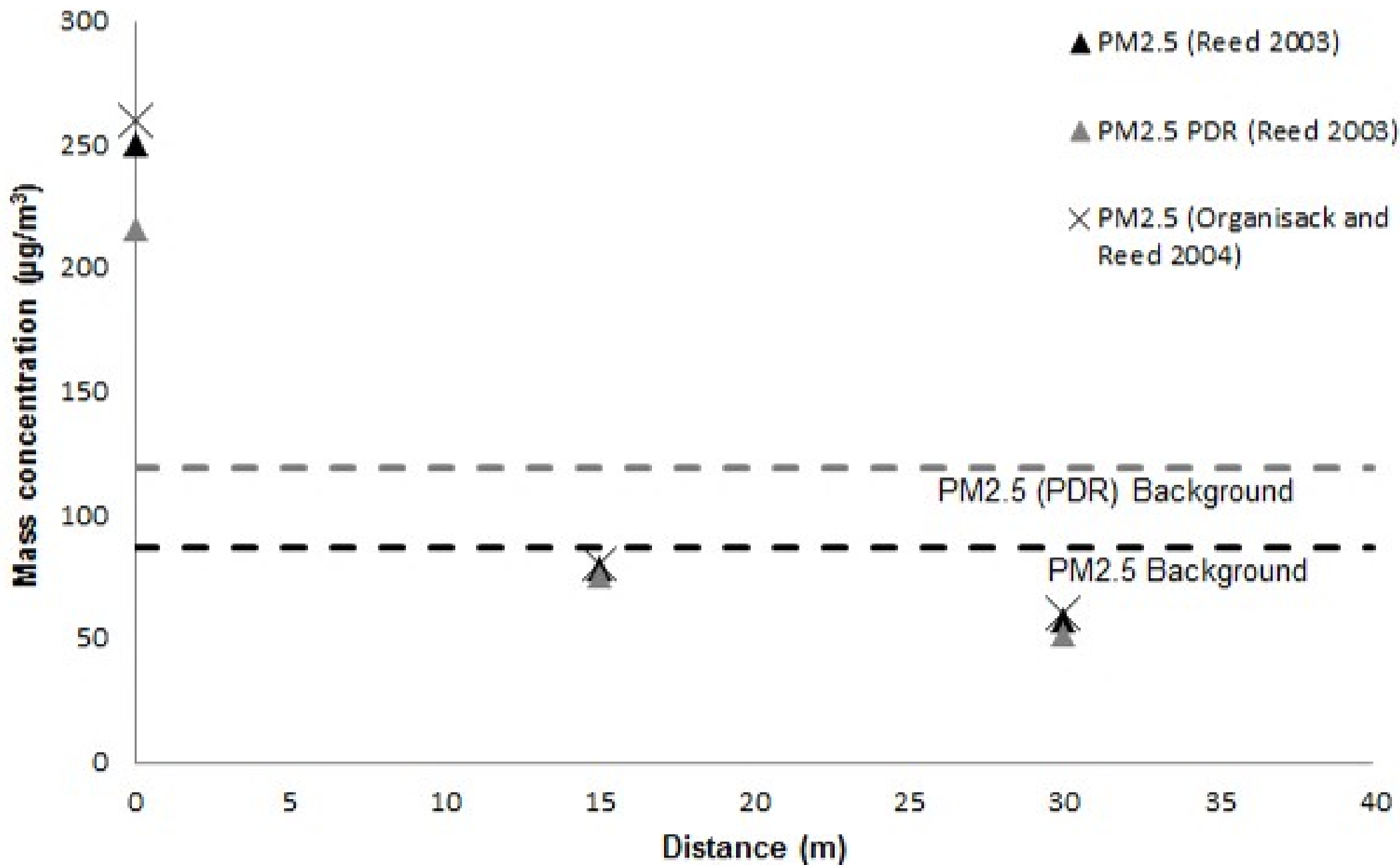
Table 1 Reviewed studies according to the main dust sources.

Main dust source	Research
Drilling	Organiscak and Page 1995 [45]
	Junttila et al. 1996 [41]
	Aatos 2003 [6]
	Golbabaei et al. 2004 [46]
	Organiscak and Page 2005 [9]
	Olusegun et al. 2009 [47]
	Bada et al. 2013 [42]
	Degan et al. 2013 [44]
	Sairanen 2014 [7]
Crushing	Junttila et al. 1996 [41]
	Junttila et al. 1997 [48]
	Almeida et al. 2002 [3]
	Chang 2004 [20]
	Sivacoumar et al. 2006 [51]
	Bahrami et al. 2008 [49]
	Olusegun et al. 2009 [47]
	Sivacoumar et al. 2009 [52]
	Chang et al. 2010 [43]
	Bluvshstein et al. 2011 [16]
	Martinsson 2011 [53]
	Saha and Padhy 2011 [50]
	Cattle et al. 2012 [54]
	Bada et al. 2013 [42]
Degan et al. 2013 [44]	
Hauling	Reed 2003 [14]
	Organiscak and Reed 2004 [55]
	Abu-Allaban et al. 2006 [56]
	Docx et al. 2007 [57]
	Chang et al. 2010 [43]
	Degan et al. 2013 [44]









Appendix A. Dust concentration and deposition results in measurements made in open pit quarries or similar sites. Concentration results given in parenthesis are the observed ranging of results.

Author	Method	Sampling time/ Duration	Setup/ Distances	Results			
				TSP ($\mu\text{g}/\text{m}^3$)	PM ₁₀ ($\mu\text{g}/\text{m}^3$)	PM _{2.5} ($\mu\text{g}/\text{m}^3$)	Deposition ($\text{g}/\text{m}^2/\text{month}$)
Drilling							
Organiscak and Page 1995 [45]	Particulate sampling trains (personal gravimetric dust sampler) Light scattering system (Real-time aerosol monitor RAM-1)	Dust concentration measurements: 2-4 h Dust abatement measurements: 1-3.5 h	Open pit coal mine Source: Immediate downwind side of the drill Ambient: Downwind at 12.2-30.5 m distance Different small rock drills: Concentration: seven drills Abatement: three drills (controlled=Ctrl) Other dust sources not reported	Source: 540-95 150 Ambient: 330-2 690 Ctrl Source: 840-2 140	N.D.	N.D.	N.D.
Junttila et al. 1996 [41]	Particulate sampling train (TSP: open face low flow sampling to membrane filter)	28-400 min	Four limestone and five dolomite quarries in Finland Occupational exposure Crushing, screening and drilling, other operations Sampling at breathing height inside the quarry Other processes (e.g. crushing) were present. Contribution to results unknown.	14 000	N.D.	N.D.	N.D.
Aatos 2003 [6]	Deposit gauges Particulate sampling trains (PM ₁₀ : Graseby-Andersen PM ₁₀ - collector) Size selective technique (PM _{2.5} : EPA PM _{2.5} -impactor)	year 2000 winter (Jan-Feb) summer (May-Jun) autumn (Oct-Nov) Deposition: one month PM ₁₀ and PM _{2.5} : 3 d, 6-8 h/d	Natural stone quarry in Finland <i>Deposition</i> : 10 gauges placed at two circles at different distances: source and ambient Source: 100-550 m Ambient: 300-850 m <i>PM₁₀ and PM_{2.5}</i> : one upwind, two downwind at the same line at different distances/ Downwind source: 50 m Downwind ambient: 100-400 m	N.D.	DW source: 77 DW ambient: 31 UW: 17	DW source: 19 DW ambient: 10 UW: 8	Source: 1.28 (0.11-13.5) Ambient: 0.29 (0.05-1.5)
Golbabaei et al. 2004 [46]	Particulate sampling trains (TSP: MSA 2G-2876 and SKC 224-PCX R3; PM ₁₀ : 10 mm cyclone)	2×4 h/d	Natural stone quarry in Iran Occupational exposure Horizontal rock drill, vertical rock drill, hammer drill, bulldozer, cutting machine	Horizontal: 79 800 Vertical: 77 800 Hammer: 107 900	Horizontal: 6 400 Vertical: 7 800 Hammer: 11 200	N.D.	N.D.
Organiscak and Page 2005	Particulate sampling trains (MSA gravimetric dust sampler)	PDR: 30 s intervals	Drilling dust abatement system development Upwind and downwind, multiple	Without: 180 With: 110	N.D.	N.D.	N.D.

[9]	Light scattering system (MIE Personal DataRAMs; PDR)		locations around the drill in two open pit quarries Other dust sources not reported Measurements with and without dust abatement system				
Olusegun et al. 2009 [47]	Light scattering system (Suspended particulate matter meter)	N.R.	Five selected quarries in Nigeria. Drilling and crushing Inside the operation area and 5m, 10m and 25 m Concentration is a composite of readings taken at four different points (cardinal directions)	N.D.	Source: 0m: 16 012 5m: 9 162 10m: 5 908 25m: 4 096	N.D.	N.D.
Bada et al. 2013 [42]	Continuous microbalance instruments (PM ₁₀ : TSI Piezobalance respirable Aerosol Mass Monitor) Light scattering systems (TSP: PPM 1005 Handheld Aerosol Monitor; PM _{2.5} : PDR-1200)	Dec 2010 3×1 h	Granite quarry in Nigeria Drilling, crushing, loading Source: Near the selected quarry operation Ambient: 5000 m	Source: 629 Ambient: 498	Source: 74 Ambient: 30	Source: 65 Ambient: <10	N.D.
Degan et al. 2013 [44]	Particulate sampling train (Pump Mod SKC 224PCEX8, aluminium cyclone and PVC filter) Light scattering system (Sensidyne nephelometer)	Two sampling campaigns: May-Jun 2012 3×2 h Jul 2012 5×2 h	Basalt quarry in Italy Drilling, primary crushing, secondary crushing, hauling During the second sampling campaign also loading Source: Near the selected quarry operation 1.5 m height	N.D.	Source: 05-06/12: 5 715 07/12: 4 110	N.D.	N.D.
Sairanen 2014 [7]	Light scattering system (Turnkey Osiris nephelometer)	15 min, 5 s intervals Two days in April 2014	Granite quarry in Finland Downwind at different distances Measurements were made at the same elevation as the drill and at higher elevation (next quarry bench) Source: 5-10 m Ambient: 15-60 m Background: measured during a longer break (over 30 min) in production	Source: 95-865 Ambient same elevation: 54-79 Ambient higher elevation: 9-77 Background: 3.4	Source: 61-673 Ambient same elevation: 44-66 Ambient higher elevation: 6-52 Background: 2.8	Source: 13-66 Ambient same elevation: 17-22 Ambient higher elevation: 2-16 Background: 1.5	N.D.
Crushing							
Junttila et al. 1996 [41]	Particulate sampling train (TSP: open face low flow sampling to membrane filter) Size selective technique (PM ₁₀ /respirable dust)	28-400 min	Four limestone and five dolomite quarries in Finland Occupational exposure Crushing, screening and drilling, other operations Sampling at breathing height inside the	Crushing: 37 000 Screening: 30 000	average 2 593- 35 556	N.D.	N.D.

	<5µm: Liquid sedimentation)		quarry Other processes (e.g. drilling) were present. Contribution to results unknown.				
Junttila et al. 1997 [48]	Particulate sampling train (TSP/total dust: open face low flow sampling to membrane filter) Size selective technique (PM ₁₀ /respirable dust <5µm: Liquid sedimentation)	25-305 min	Aggregate quarry in Finland Occupational exposure Drilling and loading sites, crushing plants screens and conveyors	29 000	9 400	N.D.	N.D.
Almeida et al. 2002 [3]	Particulate sampling train (TSP: High volume sampler) Light scattering system (PM ₁₀ and PM _{2.5} : LALLS)	4 sampling series during 5 month period 24 h sampling Limestone: Jan-May 1999 10 d/sampling series Granite: Oct-Nov 1997 and Apr-Jun 1998 7 d/sampling series	Open pit limestone mine and granite quarry in Brazil Limestone: Three samplers along the process line (source) and two samplers near the site boundary Granite: Four samplers near the site boundary PM ₁₀ and PM _{2.5} concentrations were calculated from TSP concentration via particle size distribution results	Limestone: Source: 308-1 036 Site boundary: 77-120 Granite: Site boundary: 81-242	Limestone: Source: 197 Site boundary: 35 Granite: Site boundary: 37	Limestone: Source: 52 Site boundary: 9 Granite: Site boundary: 6	N.D.
Chang 2004 [20]	Particulate sampling train (TSP: High volume sampler, PM ₁₀ : Kimoto PM ₁₀) Size selective technique (PM ₁₀ and PM _{2.5} : Anderson 10 µm inlet, PM _{2.5} impactor) Continuous microbalance system (TEOM) Deposition gauge (deposition plate)	3×1h/d 4 d/sampling series 3 sampling series in each season (spring, summer, autumn, winter)	Limestone quarry in Taiwan Concentration and size distribution at different distances inside the quarry area 4 TSP samplers operated concurrently at each sampling location and 3 sampling locations operated at the same time Source: Inside the quarry area The highest hourly concentration reported here	Source: 1 111	Source: 825	Source: 236	N.R.
Sivacoumar et al. 2006 [51]	Particulate sampling train (High volume sampler) Light scattering system (Laser diffraction particle analyzer)	Summer (Apr-May 1998) Premonsoon (Sep-Oct 1998) 30 d, 8h sampling 6a.m.-2p.m., 2p.m.-10p.m., 10p.m.-6a.m.	50 crushing units in aggregate quarry in India Source and ambient Upwind and downwind Ambient: 30-650 m from crushing units	Source: DW: 694-2 470 UW: 342-589 Ambient: DW: 143-257 UW: 86-91 Background: 30	Source: DW: 110-1 200 UW: 90-156 Ambient: DW: 48-138 UW: 39-44	Source: DW: 73-388 UW: 41-63 Ambient: DW: 24-48 UW: 17-23	N.D.
Bahrami et	Particulate sampling	Mar 2004 and Sep	29 stone crushing units in quartz quarry	Source:	N.D.	Source:	N.D.

al. 2008 [49]	trains (personal dust sampler with SKC pump and plastic cyclone)	2006	in Iran Occupational exposure 40 stationary source samplers 1.5 m height	9 460		1 240	
Olusegun et al. 2009 [47]	Light scattering system (Suspended particulate matter meter)	N.R.	Five selected quarries in Nigeria. Drilling and crushing Inside the operation area and 5m, 10m and 25 m Concentration is a composite of readings taken at four different points (cardinal directions)	N.D.	Source: 0m: 10 904 5m: 7 296 10m: 5 914 25m: 4 096	N.D.	N.D.
Sivacoumar et al. 2009 [52]	Particulate sampling train (TSP: High volume sampler) Light scattering system (CILAS 1180 model)	3 months (Jun-Aug 2006)	72 crushing units in aggregate quarry in India Source and ambient PM ₁₀ and PM _{2.5} concentrations were calculated from TSP concentration via particle size distribution results	Source: 2 759 Ambient: 190	Source: 1 010 Ambient: 70	Source: 395 Ambient: 27	N.D.
Chang et al. 2010 [43]	Particulate sampling trains (TSP: High volume sampler) Size selective technique (PM ₁₀ and PM _{2.5} : High volume sampler with impactors)	TSP: 1h PM ₁₀ and PM _{2.5} : 3h	Gravel processing site in Taiwan. Process similar to aggregate quarries Crusher, conveyor, storage pile, haul road, bare site ground Site boundary , 10 m from the crusher	Site boundary: 818 Crusher: 550	Site boundary: 373	Site boundary: 140	Dry season (06-11): 12.9-21.8 Wet season (12-05): 9.3-12.3
Bluvshstein et al. 2011 [16]	Particulate sampling trains (High volume sampler) Deposition gauge (Marble dust collector; MDCO and wet collector for comparison)	TSP; Summer Jun-Sep Deposition; May-Oct TSP: 24 h Deposition: 30 d	Limestone aggregate quarry in Israel Upwind (250 m and 2000 m), downwind (1000 m) and eastern (750 m)	DW: 80-280 UW: 30-50	N.D.	N.D.	05-08 DW: 7.9 05-08 UW: 2.1-2.4 05-08 East: 4.7 09-10 DW: 8.9 09-10 UW: 2.3-3.8 09-10 East: 7.4
Martinsson 2011 [53]	Deposition gauges (ISO/DIS 4222.2)	30 d	Two aggregate quarries in Sweden (quarries A and D) Downwind and at different directions DW: 130-400 m Different compass point around the quarry: 10 m (90° and 180°) and 30 m (270°) Background: 2 km	N.D.	N.D.	N.D.	A/90°: 2.14 A/180°: 2.75 A/270°: 116.15 A/10m: 2.14 A/200m: 1.68 A/300m: 3.27 D/130m: 1.86 D/390m: 0.86 D/400m: 0.92 Background: 0.5
Saha and Padhy 2011 [50]	Particulate sampling train (High volume sampler) Deposit gauge	Summer Rainy season Winter Ten times each	40 crushing units in aggregate quarry in India TSP Source: 20 m from crusher units Sampling equipment were placed on roof	Source: Summer: 3 490 Rainy: 2 530 Winter: 4 264	N.D.	N.D.	Source: 16 times of control Higher in the summer than in the

		season, 8 h/d	tops of single storage buildings	Background: Summer: 167 Rainy: 137 Winter: 183			winter Not measured at rainy season.
Cattle et al. 2012 [54]	Deposition gauge Size selective technique (Coulter Multisize 3)	Sep/2007 – Mar/2010 monthly 29-31 d, wet weather 60 d	Gold mine, 12 quarrying sites in Australia. Process similar to aggregate quarries 2 m height At different compass points at different distances: Trajectories 1, 2 and 3 Background G1: 700 m (source) TR1: 2 000 m, 4 000 m and 9 000 m TR2: 2 000 m, 4 000 m and 8 000 m TR3: 3 200 m and 5 700 m (Different compass point compared to TR1 and TR2) Background: 10 km	N.D.	N.D.	N.D.	G1: 4.92 TR1/2000m: 2.55 TR1/4000m: 2.28 TR1/9000m: 1.8 TR2/2000m: 2.97 TR2/4000m: 2.73 TR2/8000m: 2.16 TR3/3200m: 2.13 TR3/5700m: 1.98 Background: 1.68
Bada et al. 2013 [42]	Continuous microbalance instruments (PM ₁₀ : TSI Piezobalance respirable Aerosol Mass Monitor) Light scattering systems (TSP: PPM 1005 Handheld Aerosol Monitor; PM _{2.5} : PDR- 1200)	Dec 2010 Three times 1 h	Granite quarry in Nigeria Drilling, crushing, loading Source: Near the selected quarry operation Ambient: 5000 m	Source: 3 545 Ambient: 498	Source: 231 Ambient: 30	Source: 130 Ambient: <10	N.D.
Degan et al. 2013 [44]	Particulate sampling train (Pump Mod SKC 224PCEX8, aluminium cyclone and PVC filter) Light scattering system (Sensidyne nephelometer)	Two sampling campaigns: May-Jun 2012 3×2 h Jul 2012 5×2 h	Basalt quarry in Italy Drilling, primary crushing, secondary crushing, hauling During the second sampling campaign also loading Source: Near the selected quarry operation 1.5 m height	N.D.	Source: 05-06/12: Primary: 4 385 Secondary: 5 315 07/12: Primary: 4 510 Secondary: 5 480	N.D.	N.D.
Hauling							
Reed 2003 [14]	Particulate sampling trains (MSHA Escort ELF personal sampler and cyclone) Light scattering systems (RAM's personal sampler; PDR)	Year 2002 6-7h 2s interval in PDR	Aggregate (limestone) quarry in USA Two adjacent lines downwind Upwind DW: 0 m, 15 m and 30 m UW: 0 m	DW/0m: 2 970 DW/15m: 910 DW/30m: 570 UW: 1 080	DW/0m: 1 030 DW/15m: 270 DW/30m: 150 UW: 460	DW/0m: 250 DW/15m: 78 DW/30m: 58 UW: 87 PDR: DW/0m: 220	N.D.

	Size selective techniques (cascade impactor)					DW/15m: 76 DW/30m: 52 UW: 120	
Organiscak and Reed 2004 [55]	Particulate sampling trains (MSHA ELF personal sampler and cyclones BGI, Inc. GK2.69 and Dorr-Oliver 10 mm nylon) Light scattering systems (Thermo-Anderson/MIE Personal Data RAMs; PDR)	Jul-Aug 2002 During 3 d shifts for each operation PDR: 2s	Aggregate (limestone) quarry in USA Two adjacent lines downwind Upwind 1.5 m height DW: 0 m, 15 m and 30 m UW: 0 m	DW/0m: 2 980* DW/15m: 920* DW/30m: 580* UW: 1 090*	DW/0m: 1 030* DW/15m: 270* DW/30m: 160* UW: 460*	DW/0m: 260* DW/15m: 80* DW/30m: 60* UW: 90*	N.D.
Abu-Allaban et al. 2006 [56]	Light scattering systems (DustTrak Aerosol Monitor Model 8520)	5 400s 60s interval	Limestone quarry in Jordan Downwind 2 m above a haul road	N.D.	630	N.D.	N.D.
Docx et al. 2007 [57]	Deposit gauge (Cylindrical adhesive pad particulate sampler and optical image analysis; IA)	17 Aug 2005 11:30-15:30 local time 3 periods of sampling	Aggregate (limestone) quarry in UK Adjacent line with three downwind and three upwind samplers 1.5 m height Distances: 3 m, 16 m and 29 m	DW/3m: 1 370* DW/16m: 560* DW/29m: 380* UW/29m: 350*	N.D.	N.D.	N.D.
Chang et al. 2010 [43]	Particulate sampling trains (TSP: High volume sampler) Size selective technique (PM ₁₀ and PM _{2.5} : High volume sampler with impactors)	TSP: 1h PM ₁₀ and PM _{2.5} : 3h	Gravel processing site in Taiwan. Site boundary Crusher, conveyor, storage pile, haul road, bare site ground 10 m	Haul road: 1 560	Haul road: 1 130	N.D.	N.D.
Degan et al. 2013 [44]	Particulate sampling train (Pump Mod SKC 224PCEX8, aluminium cyclone and PVC filter) Light scattering system (Sensidyne nephelometer)	Two sampling campaigns: May-Jun 2012 3×2 h Jul 2012 5×2 h	Basalt quarry in Italy Drilling, primary crushing, secondary crushing, hauling During the second sampling campaign also loading Source: Near the selected quarry operation 1.5 m height	N.D.	05-06/12: 4 332 07/12: 4 265	N.D.	N.D.

N.D. = Not detected

N.R = Not reported

DW = Downwind

UW = Upwind

* = Concentrations were interpret / construed from the figures

Appendix B. Emission factors.

Author	Settlement	Source	Unit	Emission factor		
				TSP	PM ₁₀	PM _{2.5}
US EPA 2004b [5]	Different processes in several aggregate quarries EPA Method 201A	Tertiary crushing	kg/tn	0.0027	0.0012	N.D.
		Tertiary crushing – controlled	kg/tn	0.0006	0.00027	0.00005
		Fines crushing	kg/tn	0.0195	0.0075	N.D.
		Fines crushing - controlled	kg/tn	0.0015	0.0006	0.000035
		Screening	kg/tn	0.0125	0.0043	N.D.
		Screening - controlled	kg/tn	0.0011	0.00037	0.000025
		Fines screening	kg/tn	0.15	0.036	N.D.
		Fines screening- controlled	kg/tn	0.0018	0.0011	N.D.
		Conveyor transfer point	kg/tn	0.0015	0.00055	N.D.
		Conveyor transfer point-controlled	kg/tn	0.00007	2.3x10 ⁻⁵	6.5x10 ⁻⁶
		Wet drilling (unfragmented stone)	kg/tn	N.D.	4.0x10 ⁻⁵	N.D.
		Truck loading (fragmented stone)	kg/tn	N.D.	8.0x10 ⁻⁶	N.D.
		Truck loading (crushed stone)	kg/tn	N.D.	5.0x10 ⁻⁵	N.D.
Chang et al. 2010 [43]	Crushing gravel in Taiwan Particulate sampling trains (TSP: High volume sampler) Size selective technique (PM ₁₀ and PM _{2.5} : High volume sampler with impactors)	Loading/ unloading gravel	kg/tn	0.74	0.48	0.23
		Loading/ unloading crushed material	kg/tn	0.85	0.56	0.35
		Bare ground	kg/tn	0.095	0.066	0.034
		Unpaved roads	kg/tn	1.18	0.71	0.32
Aatos 2003 [6]	Drilling at natural stone quarry in Finland Particulate sampling trains (PM ₁₀ : Graseby- Andersen PM ₁₀ collector) Size selective technique (PM _{2.5} : EPA PM _{2.5} - impactor)	Overall quarry	g/s	N.D.	0.213 – 0.504	0.035 – 0.153
Chackraborty et al. 2002 [59]	Crushing at aggregate quarries in India (three iron ore mines) US EPA Method Particulate sampling trains (High volume sampler)	Drilling*	g/s	0.3433	N.D.	N.D.
		Loading overburden or mineral*	g/s	0.1963 - 0.3317	N.D.	N.D.
		Unloading overburden or mineral*	g/s	0.5036 - 0.7651	N.D.	N.D.
		Overall quarry*	g/s	4.4688 - 5.1496	N.D.	N.D.

N.D. = Not detected

* Emission factor was represented as equation. Emission factor was calculated with average values of equation variables. Variables in the equation were moisture, silt content and wind speed.